Dynamic Model Based Vector Control of Linear Induction Motor

Valerie Rafalko and Arthur Rimmele
Naval Air Warfare Center
Aircraft Division
Lakehurst, NJ

Qing Dong
Naval Surface Warfare Center
Carderock Division
Philadelphia, PA

Saroj Biswas
Temple University
Dept of Elec and Comp Engineering
Philadelphia, PA

***Abstract*—Induction machines (IM) have been the work-horse of industry due to their robustness, simple and rugged structure, low cost and reliability. Traditionally, AC machines have been used in open-loop constant speed applications. The linear induction motor (LIM) is an alternative formation of a rotational induction machine (RIM). Typically, the LIM is designed for high force and stroke motion applications, such as material handling and transportation systems. Often a LIM moves along a linear rail directly, so it provides precision positioning tracking performance and high dynamic stiffness with a hard stop when equipped with a linear encoder and closed-loop control methods. A variable frequency vector control is the foundation of modern high performance AC drives for rotary induction motors. The driving principles of the LIM are similar to the RIM, but its control characteristics are more complicated than the RIM. When driven by a field-oriented controller, also known as a vector controller, LIM behaves like a separately excited DC machine where flux and motion dynamics are controlled independently in order to achieve high performance from the IM drives. The vector control method provides velocity and position control of a LIM effectively. In this paper, a mathematical model of a linear induction motor is presented based on the synchronous *d-q* reference frame. The secondary field oriented vector control strategy is developed for precise force control to achieve the desired speed profile for varying load conditions. Under the developed control scheme, the controller stabilizes the LIM effectively when the mass of the slider is varying. The effectiveness of the proposed control scheme is verified by simulation examples.**

I. Introduction

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. The physical principle behind the electric motor is the interactions of an electric current and a magnetic field. Electric motors can be divided into two types: alternating current (AC) electric motors and direct current (DC) electric motors. AC induction machines (IM) have been the work-horse of industry and widely used in U.S. Navy shipboard machinery due to their robustness, simple and rugged structure, low cost and reliability. Traditionally, AC machines have been used in open-loop constant speed applications. Their dynamic behavior becomes more complex in closed-loop variable speed drives. Much research and development has been conducted to develop comprehensive power electronic inverters and advanced AC induction machine control methods. In recent years, many research efforts have been made to control an AC machine speed following the concepts of a DC machine.

All mechanisms involve some kind of motion [1], [2]. Mechanical motions can be categorized into linear motion, rotary motion, intermittent motion, oscillating motion, reciprocating motion and irregular motion. Mechanisms can be used to convert one form of motion into another. For instance, a rack and pinion mechanism converts rotational motion into linear motion. Mechanical motion conversion devices complicate the machinery design and introduce mechanical losses.

A linear motor (LM) is a special electrical motor designed to produce force in a straight line. The construction of a linear motor is close to that of a standard rotating motor, but in a linear form. There are several key advantages of using linear induction motors (LIM). As the stator and rotor are not in physical contact with one another, operation is relatively silent, and frictional wear of the motor system is reduced, which combine to give greatly reduced maintenance costs.

The LIM is an alternative formation of a rotational induction machine (RIM). An essential feature that distinguishes the LIM from the traditional rotary motor is the linear motion of the moving member, called slider. Typically, the LIM is designed for high force and stroke motion applications, such as material handling and transportation systems. Often a LIM moves along a linear rail directly, so it provides precision in position tracking performance and high dynamic stiffness with a hard stop when equipped with a linear encoder and closed-loop control methods. Primarily, a variable frequency vector control is the foundation of modern high performance AC drives for rotary induction motors. Many control techniques have been developed based on this principle [3]–[7]. A variable frequency inverter is usually required to provide velocity control of a LIM. A LIM equipped with a linear encoder can do point-to-point programmable positioning when driven with a vector control and motion controller [8], [9].

In [10], a control method for magnetic levitation vehicles has been developed using linear induction motors which can generate both thrust and attractive force. In this control method, voltage vectors of pulse-width modulation (PWM) inverters were appropriately selected and controlled with decoupling of the thrust and attractive force.

With a modest amount of modeling effort, a feedback-

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**
4. TITLE AND SUBTITLE **Dynamic Model Based Vector Control Of Linear Induction Motor**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Air Warfare Center,Aircraft Division,Lakehurst,NJ,08733**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

1/20, Presented at American Society of Naval Engineers (ASNE) Electric Machines Technology Symposium (EMTS) 2012, May 23-24, 2012, Philadelphia, PA

14. ABSTRACT

Induction machines (IM) have been the workhorse of industry due to their robustness, simple and rugged structure, low cost and reliability. Traditionally, AC machines have been used in open-loop constant speed applications. The linear induction motor (LIM) is an alternative formation of a rotational induction machine (RIM). Typically, the LIM is designed for high force and stroke motion applications, such as material handling and transportation systems. Often a LIM moves along a linear rail directly, so it provides precision positioning tracking performance and high dynamic stiffness with a hard stop when equipped with a linear encoder and closed-loop control methods. A variable frequency vector control is the foundation of modern high performance AC drives for rotary induction motors. The driving principles of the LIM are similar to the RIM, but its control characteristics are more complicated than the RIM. When driven by a field-oriented controller, also known as a vector controller, LIM behaves like a separately excited DC machine where flux and motion dynamics are controlled independently in order to achieve high performance from the IM drives. The vector control method provides velocity and position control of a LIM effectively. In this paper, a mathematical model of a linear induction motor is presented based on the synchronous d-q reference frame. The secondary field oriented vector control strategy is developed for precise force control to achieve the desired speed profile for varying load conditions. Under the developed control scheme,the controller stabilizes the LIM effectively when the mass of the slider is varying. The effectiveness of the proposed control scheme is verified by simulation examples.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

feedforward control structure has been proposed for precision motion control of a permanent magnet linear motor for applications which are inherently repetitive in terms of the motion trajectories [11]. Three separate controllers: a backstepping adaptive controller, a self-tuning adaptive controller and a model reference adaptive controller were designed [12]. These controllers were implemented on a PC-based position control system to execute several experiments, including transient responses, load disturbance responses, and tracking responses for performance comparison. In addition, sensorless control is critical for LIM control in some special case. Reference [13] introduces a direct torque and flux control based on space-vector modulation for induction motor sensorless drives. Yamamura [14] introduced a particular end effect phenomenon which is a crucial issue for a LIM. There have been many proposed solutions proposed that address sensorless control and end effect control [15], [16].

In this paper, a mathematical model centered on the synchronous *d*-*q* reference frame is presented to analyze the LIM. The velocity closed-loop method and the secondary field oriented vector control strategy are developed and simulated based on the developed mathematical model. The effectiveness of the proposed control scheme is verified by simulated results.

The rest of the paper is organized as follows. Section II presents a mathematical model based on the synchronous *d*-*q* reference frame. In Section III, the basic structure of vector control is introduced. Proportional-Integral (PI) control is incorporated into vector control to achieve the LIM's velocity and position control. Numerical simulation results are provided to demonstrate the effectiveness of the vector control scheme on a LIM. Conclusions are drawn in Section V.

II. Modeling

In order to understand the performance and to design a controller for the linear induction motor, it is necessary to first introduce its dynamic model. The commonly used framework for the dynamic model of a linear induction motor is based on the synchronous reference frame corresponding to the frequency of the applied voltage. The method is very similar to that used for modeling a three phase rotary induction motor, however with few modifications. There are few assumptions to be made as follows:

1) Only stator variables are measurable
2) No end-effect is considered
3) No friction is considered
4) Three phases of the LIM are balanced
5) The magnetic circuit is unsaturated

In the rest of the paper, the following symbols for various parameters and variables are used:

R_s	primary winding resistance
R_r	secondary resistance
L_m	magnetizing inductance
L_s	primary inductance
L_r	secondary inductance
i_{sd}	d-axis primary current
i_{sq}	q-axis primary current
V_{sd}	d-axis primary voltage
V_{sq}	q-axis primary voltage
T_r	secondary time constant, $T_r = \frac{L_r}{R_r}$
σ	the leakage coefficient, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$
v_e	the synchronous linear velocity
v	the slider linear velocity
h	pole pitch
λ_{rd}	d-axis secondary flux
λ_{rq}	q-axis secondary flux
K_f	the force constant, $K_f = \frac{3\pi L_m}{2hL_r}$
F_e	the electromagnetic force
F_L	the external force, i.e. disturbance
M	total mass of the slider
D	the viscous friction

Dynamic analysis of induction motors in conveniently done in the *d*-*q* reference frame. It allows the torque and the flux in the machine to be controlled independently under dynamic conditions, in contrast to analysis based on the *a*-*b*-*c* phase quantities. In this study, end effects are neglected; the readers are referred to [17] and [9] for *d*-*q* model of the equivalent electrical circuit with end effects. Fig. 1 shows the *d*-*q* equivalent circuit representation of the rotary induction motor.

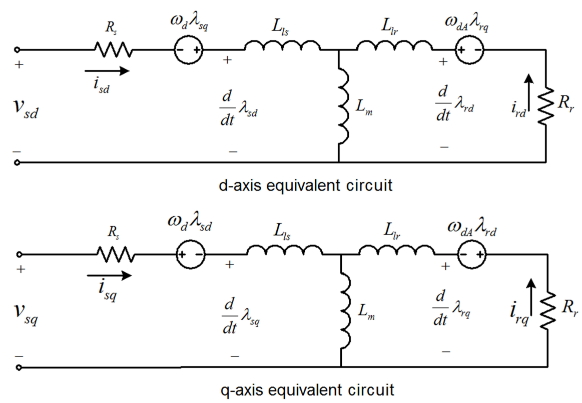

Fig. 1. *d*-*q* equivalent circuit of the LIM excluding the end effects

Note that the rotor has a closed circuit with no external applied voltage. The relations between the primary and secondary fluxes and the currents in stationary reference frame can be written as followings:

$$\begin{aligned} \lambda_{sq} &= L_S i_{sq} + L_m i_{rq} \\ \lambda_{sd} &= L_S i_{sd} + L_m i_{rd} \\ \lambda_{rq} &= L_r i_{rq} + L_m i_{sq} \\ \lambda_{rd} &= L_r i_{rd} + L_m i_{sd} \end{aligned} \tag{1}$$

The three phase voltage applied to the LIM establishes a magnetic field that has a synchronous translational speed, v_e, of

$$\omega_e = \frac{\pi}{h} v_e \tag{2}$$

where h is the pole pitch, which defines the linear distance between two consecutive poles, and ω_e is the applied frequency. By induction, a voltage is induced in the slider which interacts with the primary magnetic field to propel the slider in the same direction. Following the concepts on induction motors, the slider speed, v, is always slightly less than the synchronous speed. The slip frequency is denoted as

$$\begin{aligned} \omega_{dA} &= \omega_e - \omega_r \\ &= \frac{\pi}{h}(v_e - v) \end{aligned} \tag{3}$$

Following the d-q equivalent circuit, the dynamic equations of the LIM are expressed in a synchronous reference frame aligned to the rotor flux as:

$$v_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_d \lambda_{sq} \tag{4}$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} + \omega_d \lambda_{sq} \tag{5}$$

$$\cancelto{0}{v_{rd}} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{dA} \lambda_{rq} \tag{6}$$

$$\cancelto{0}{v_{rq}} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} + \omega_{dA} \lambda_{rd} \tag{7}$$

where $\omega_{dA} = \omega_{\text{slip}}$ and $\omega_d = \omega_{\text{syn}}$.

The complete dynamic model of the LIM is then obtained by combining the above equations, and is given by [18], [19]:

$$\begin{aligned} \frac{di_{sq}}{dt} &= -\frac{\pi}{h} v_e i_{sd} - \left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{sq} \\ &\quad - \frac{L_m \pi}{\sigma L_s L_r h} v \lambda_{rd} + \frac{L_m}{\sigma L_s L_r T_r}\lambda_{rq} + \frac{1}{\sigma L_s} V_{sq} \end{aligned} \tag{8}$$

$$\begin{aligned} \frac{di_{sd}}{dt} &= -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{sd} + \frac{\pi}{h} v_e i_{sq} \\ &\quad + \frac{L_m}{\sigma L_s L_r T_r}\lambda_{rd} + \frac{L_m \pi}{\sigma L_s L_r h} v \lambda_{rq} + \frac{1}{\sigma L_s} V_{sd} \end{aligned} \tag{9}$$

$$\frac{d\lambda_{rq}}{dt} = \frac{L_m}{T_r} i_{sq} - \frac{\pi}{h}(v_e - v)\lambda_{rd} - \frac{1}{T_r}\lambda_{rq} \tag{10}$$

$$\frac{d\lambda_{rd}}{dt} = \frac{L_m}{T_r} i_{sd} + \frac{\pi}{h}(v_e - v)\lambda_{rq} - \frac{1}{T_r}\lambda_{rd} \tag{11}$$

The motion of the slider is governed by the Newton's law of motion, i.e., balance of various forces acting on it. As such, it has

$$F_e = K_f(\lambda_{rd} i_{sq} - \lambda_{rq} i_{sd}) \tag{12}$$

$$\quad = \frac{d}{dt}(Mv) + Dv + F_L \tag{13}$$

where the first equation gives the electromagnetic force developed by the machine, which balances the mechanical forces based on the Newton's laws. Note that the external force in equation (13) is omitted in this paper, $F_L = 0$.

III. Vector Control

The driving principles of the LIM are similar to that of the rotary induction motor, however its control characteristics are more complicated. When driven by a field-oriented controller, also known as a vector controller, LIM behaves like a separately excited DC machine where flux and motion dynamics are controlled independently in order to achieve high performance from the LIM drives. The vector control method provides velocity and position control of a LIM effectively.

It is clear from equation (12) that if the secondary flux λ_{rq} can be maintained at zero, then the developed force, F_e, would be directly proportional to the current, i_{sq}, so that the machine basically would behave like a DC motor. Then, the current i_{sq} can be controlled to generate the required force for a given load. This approach offers precise control of performance, which is otherwise not possible using only voltage or frequency control methods.

The aim of the field oriented control is to maintain a constant secondary d-axis flux and make the secondary q-axis flux null, i.e., to maintain $\lambda_{rq} = 0$ and $\frac{d\lambda_{rq}}{dt} = 0$ for all time. This can be achieved by controlling the line frequency as well as by varying the applied voltage to the motor as shown below:

$$V_{sd} = R_s I_{sd} - \sigma L_s \omega_e I_{sq} \tag{14}$$

$$V_{sq} = R_s I_{sq} + L_s \omega_e I_{sd} \tag{15}$$

$$\omega_e = \frac{\pi}{h} v + \frac{R_r}{L_r}\frac{I_{sq}}{I_{sd}} \tag{16}$$

The complete schematic of the closed loop system is shown in Fig. 2:

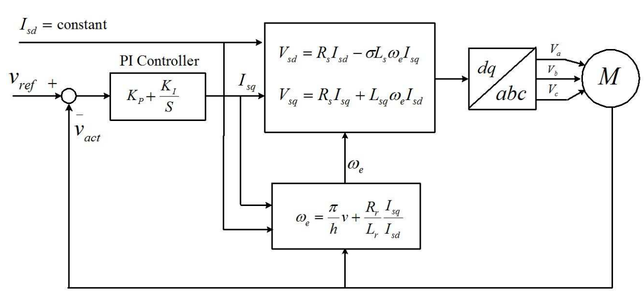

Fig. 2. PI vector control of the LIM

The above control scheme uses two control currents, I_{sd} and I_{sq}. In this research, the flux current I_{sd} is assumed constant at the open loop nominal operation of the motor, however can also be controlled separately to maintain a desired flux level in the machine. The force current I_{sq} is proportional to the load which is regulated using a PI controller shown in the Fig. 3.

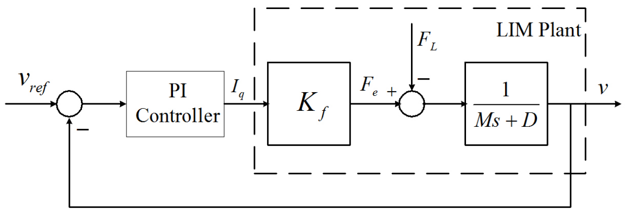

Fig. 3. PI vector control of the LIM

IV. Simulation

The response of a typical LIM is investigated through Matlab simulation in three cases. Open-loop simulation was performed in the first case to understand the operation of the linear induction motor for a constant applied voltage at the line frequency. For all simulations, the following parameters are used:

R_s=5.3685Ω	R_r=3.5315 Ω	L_m=0.02419 H
L_s=0.02846 H	L_r=0.02846 H	h=0.027 m
M=2.78 kg	D=36.0455	V_a= 180 V

It is assumed that the slider is carrying a load mass which is 50 times larger than the mass of the slider. Fig. 4 depicts the velocity of the LIM slider (without carrying any load mass) under open loop operation with a constant voltage constant frequency operation. Here the desired slider speed is 3 m/sec, which is clearly not achieved. Fig. 5 and Fig. 6 show that the secondary fluxes λ_{rq} and λ_{rd}. Clearly the secondary flux λ_{rq} is not equal to 0 which is desired for precise force control. The motor primary current is shown in Fig. 7.

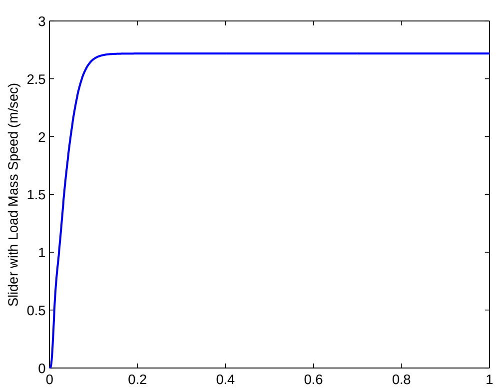

Fig. 4. Slider speed profile (open-loop control)

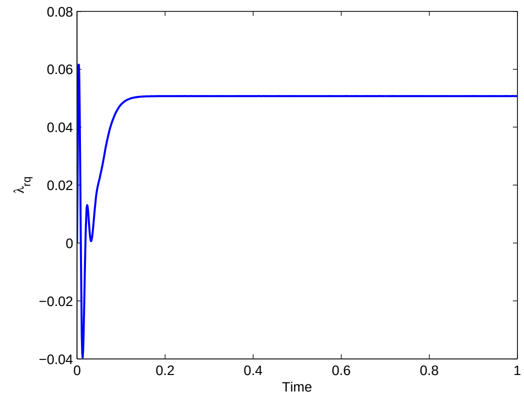

Fig. 5. λ_{rq} profile (open-loop control)

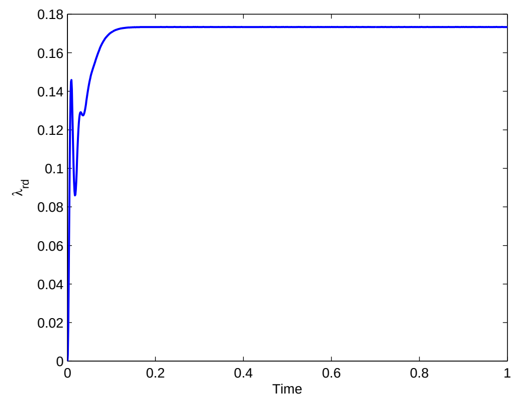

Fig. 6. λ_{rd} profile (open-loop control)

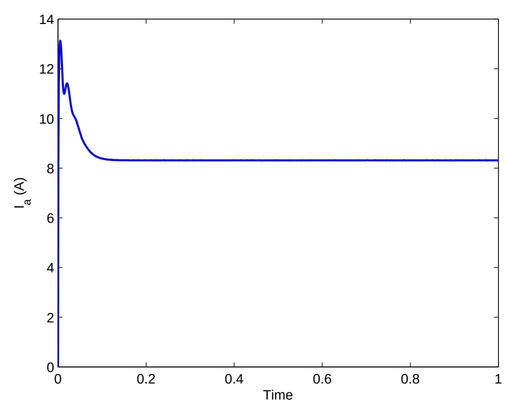

Fig. 7. I_a profile (open-loop control)

The next simulation shows the response of the linear induction motor carrying a load mass with a constant applied voltage and the load mass is released after two seconds. As expected, the slider and the load mass are not able to accelerate to a reference speed within desired time period. Then at $t = 2$ seconds, the load mass is released, and as expected the slider speed increases to a higher value. Transient variations in line

current is shown in Fig. 8 and fluxes as shown in Fig. 9 and Fig. 10. It is clear that the linear motor speed performance is not achieved as shown in Fig. 11. Therefore, a vector control method needs to be applied to regulate the slider speed as well as to have better response to force commands.

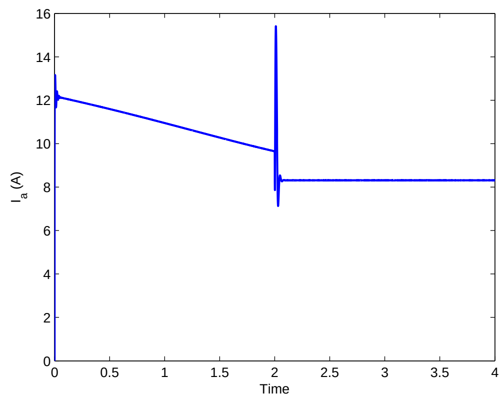

Fig. 8. I_a profile with load mass released at $t = 2$ sec (open-loop control)

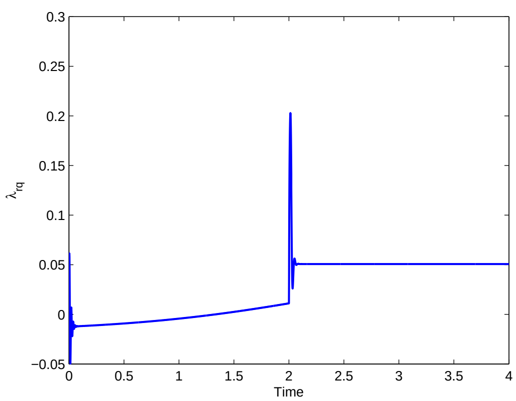

Fig. 9. λ_{rq} profile with load mass released at $t = 2$ sec (open-loop control)

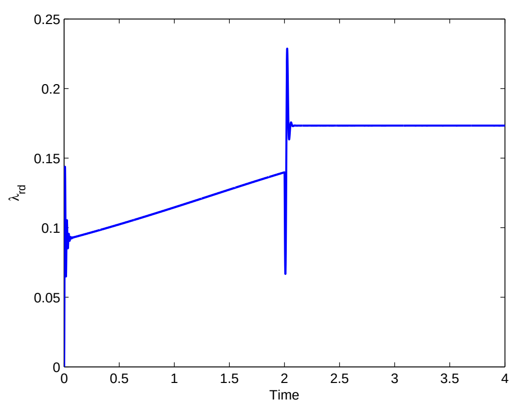

Fig. 10. λ_{rd} profile with load mass released at $t = 2$ sec (open-loop control)

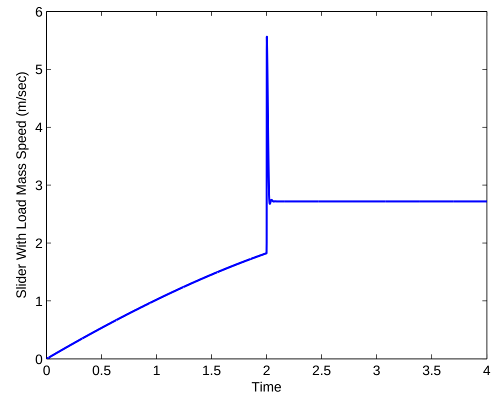

Fig. 11. Slider speed profile with load mass released at $t = 2$ sec (open-loop control)

Next, a PI controller is designed within the vector control loop to regulate the force current, I_{sq}. The design requirements are that the LIM slider carries a load mass and accelerates in the first two second. The slider and the load mass should reach the speed reference of 3 m/s at the end of the two seconds. The load mass is then released from the slider. The performed simulation is based on selected PI control gains of $K_p = 35$ and $K_I = 75$. Fig. 12 shows the simulated slider speed profile under the appropriate PI vector controller. Fig. 13 shows that λ_{rq} approaches zero when the vector control is applied. Fig. 14 also shows that the secondary flux λ_{rd} is maintained at constant value. Fig. 15 and Fig. 16 show the variations in applied voltage and the line frequency that are essential in vector control method. Note that the slider speed remains constant after the load mass is released as shown in Fig. 12.

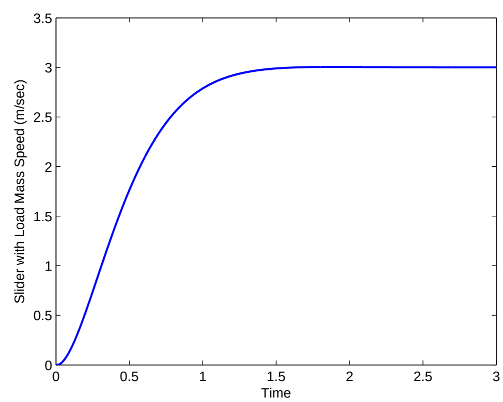

Fig. 12. Slider speed profile with load mass released at $t = 2$ sec (closed-loop vector control)

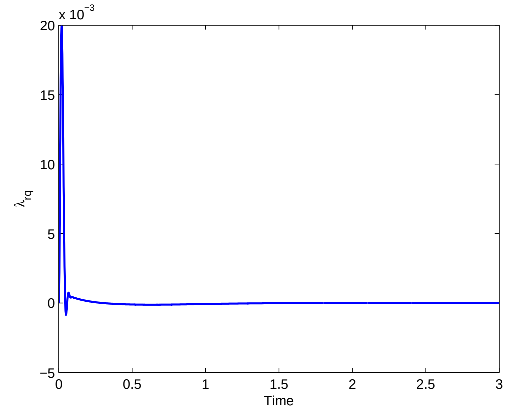

Fig. 13. λ_{rq} profile with load mass released at $t = 2$ sec (closed-loop vector control)

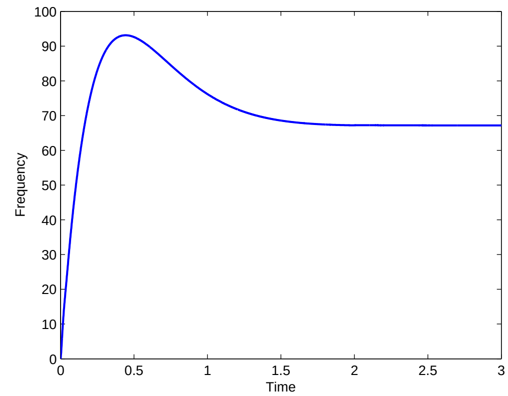

Fig. 16. Frequency profile with load mass released at $t = 2$ sec (closed-loop vector control))

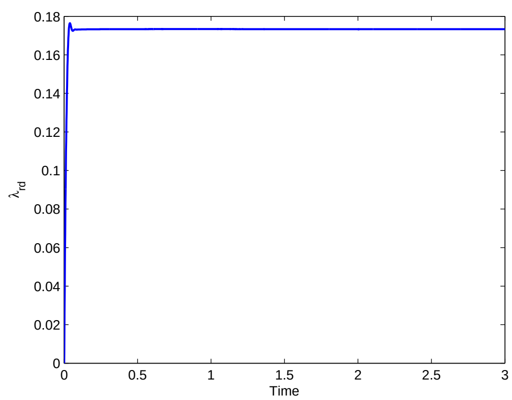

Fig. 14. λ_{rd} profile with load mass released at $t = 2$ sec (closed-loop vector control)

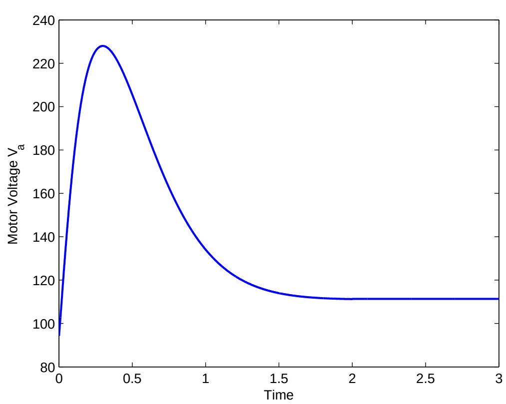

Fig. 15. V_a profile with load mass released at $t = 2$ sec (closed-loop vector control)

In some cases, it is required to stop the slider after it releases the load mass. To achieve such task, a zero speed reference command can be applied at 2.25 seconds and the slider slows down to a complete stop at six seconds under the same PI vector control scheme. The simulated speed profile is illustrated in Fig. 17. In summary, the speed of the LIM can be regulated via vector control method. A control scheme, such as the closed loop control or the trajectory following open loop control can be developed correspondingly to effectively manage the performance of the LIM to satisfy the operation requirements.

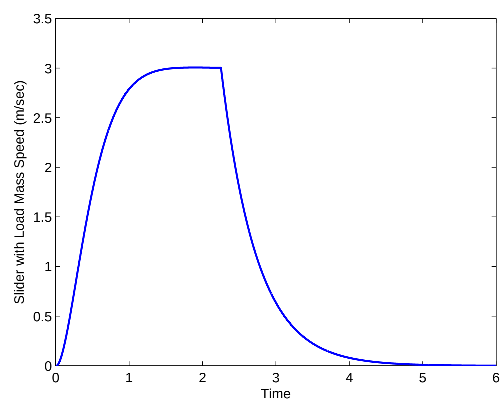

Fig. 17. Slider speed profile with load mass released at $t = 2$ sec and stopped at $t = 6$ sec (closed-loop vector control)

V. Conclusion

This paper briefly introduced the dynamic model of an AC linear induction motor based on the model of an AC induction rotary motor. A circuit equivalent was presented for linear induction motor model representation. The developed model can be further expanded to include linear motor dynamic end effects. Simple PI vector control was considered to achieve the desired velocity profile with an applied constant voltage

command input. The controller was able to stabilize the linear motor under varying payload condition when proper PI gains are chosen. Future work includes model development and vector control design taking account of end effects of the linear motor.

REFERENCES

[1] C. Wilson, J. Sadler, and W. Michels, *Kinematics and dynamics of machinery*. Pearson Education, 2003.

[2] F. Reuleaux, *The kinematics of machinery: outlines of a theory of machines*. Macmillan, 1876.

[3] C. Schauder, "Adaptive speed identification for vector control of induction motors without rotational transducers," *Industry Applications, IEEE Transactions on*, vol. 28, no. 5, pp. 1054–1061, 1992.

[4] J. Nash, "Direct torque control, induction motor vector control without an encoder," *Industry Applications, IEEE Transactions on*, vol. 33, no. 2, pp. 333–341, 1997.

[5] G. Sousa, B. Bose, and J. Cleland, "Fuzzy logic based on-line efficiency optimization control of an indirect vector-controlled induction motor drive," *Industrial Electronics, IEEE Transactions on*, vol. 42, no. 2, pp. 192–198, 1995.

[6] L. Harnefors and H. Nee, "A general algorithm for speed and position estimation of ac motors," *Industrial Electronics, IEEE Transactions on*, vol. 47, no. 1, pp. 77–83, 2000.

[7] J. Holtz and J. Quan, "Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification," *Industry Applications, IEEE Transactions on*, vol. 38, no. 4, pp. 1087–1095, 2002.

[8] F. Lin, P. Shen, and S. Hsu, "Adaptive backstepping sliding mode control for linear induction motor drive," in *Electric Power Applications, IEE Proceedings-*, vol. 149, no. 3. IET, 2002, pp. 184–194.

[9] E. Da Silva, E. Dos Santos, P. Machado, and M. De Oliveria, "Vector control for linear induction motor," in *Industrial Technology, 2003 IEEE International Conference on*, vol. 1. IEEE, 2003, pp. 518–523.

[10] I. Takahashi and Y. Ide, "Decoupling control of thrust and attractive force of a lim using a space vector control inverter," *Industry Applications, IEEE Transactions on*, vol. 29, no. 1, pp. 161–167, 1993.

[11] K. Tan, H. Dou, Y. Chen, and T. Lee, "High precision linear motor control via relay-tuning and iterative learning based on zero-phase filtering," *Control Systems Technology, IEEE Transactions on*, vol. 9, no. 2, pp. 244–253, 2001.

[12] T. Liu, Y. Lee, and Y. Crang, "Adaptive controller design for a linear motor control system," *Aerospace and Electronic Systems, IEEE Transactions on*, vol. 40, no. 2, pp. 601–616, 2004.

[13] C. Lascu, I. Boldea, and F. Blaabjerg, "A modified direct torque control for induction motor sensorless drive," *Industry Applications, IEEE Transactions on*, vol. 36, no. 1, pp. 122–130, 2000.

[14] S. Yamamura, "Theory of linear induction motors," *New York, Halsted Press, 1979. 246 p.*, vol. 1, 1979.

[15] G. Kang and K. Nam, "Field-oriented control scheme for linear induction motor with the end effect," in *Electric Power Applications, IEE Proceedings-*, vol. 152, no. 6. IET, 2005, pp. 1565–1572.

[16] M. Tsuji, S. Chen, K. Izumi, and E. Yamada, "A sensorless vector control system for induction motors using q-axis flux with stator resistance identification," *Industrial Electronics, IEEE Transactions on*, vol. 48, no. 1, pp. 185–194, 2001.

[17] J. Sung and K. Nam, "A new approach to vector control for a linear induction motor considering end effects," in *Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE*, vol. 4. IEEE, 1999, pp. 2284–2289.

[18] R. Krishnan, *Electric motor drives: modeling, analysis, and control*. Prentice Hall Upper Saddle River, NJ, 2001, vol. 1.

[19] F. Lin and R. Wai, "Hybrid control using recurrent fuzzy neural network for linear induction motor servo drive," *Fuzzy Systems, IEEE Transactions on*, vol. 9, no. 1, pp. 102–115, 2001.